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DC Grids for Smart LED-Based Lighting: The EDISON Solution

Steffen Thielemans [1,2], Dario Di Zenobio [3], Abdellah Touhafi [3], Philippe Lataire [4] and Kris Steenhaut [1,2,3,*]

[1] Department of Electronics and Informatics (ETRO), Vrije Universiteit Brussel (VUB), Pleinlaan 2, B1050 Brussels, Belgium; sthielem@etrovub.be
[2] Interuniversity Microelectronics Centre (IMEC), Kapeldreef 75, B3001 Leuven, Belgium
[3] Department of Engineering Technology (INDI), Vrije Universiteit Brussel (VUB), Pleinlaan 2, B1050 Brussels, Belgium; dario.di.zenobio@vub.be (D.D.Z.); abdellah.touhafi@vub.be (A.T.)
[4] Department of Electric Engineering and Energy Technology (ETEC), Vrije Universiteit Brussel (VUB), Pleinlaan 2, B1050 Brussels, Belgium; philippe.lataire@vub.be
* Correspondence: ksteenha@etrovub.be; Tel.: +32-2-629-2977

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Abstract: This paper highlights the benefits and possible drawbacks of a DC-based lighting infrastructure for powering Light Emitting Diode (LED)-lamps. It also evaluates the efforts needed for integrating the so called smart lighting and other sensor/actuator based control systems, and compares existing and emerging solutions. It reviews and discusses published work in this field with special focus on the intelligent DC-based infrastructure named EDISON that is primarily dedicated to lighting, but is applicable to building automation in general. The EDISON "PowerLAN" consists of a DC-based infrastructure that offers telecommunication abilities and can be applied to lighting retrofitting scenarios for buildings. Its infrastructure allows simple and efficient powering of DC-oriented devices like LED lamps, sensors and microcontrollers, while offering a wired communication channel. This paper motivates the design choices for organizing DC lighting grids and their associated communication possibilities. It also shows how the EDISON based smart lighting solution is evolving today to include new communication technologies and to further integrate other parts of building management solutions through the OneM2M (Machine to Machine) service bus.

Keywords: DC-grid; lighting control; LED drivers; power line communication; OneM2M; IoT; wireless sensor networks; lighting; building automation; RESTful

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1. Introduction

In the mission to reduce greenhouse gas emissions, the European Union enacted the "2030 climate and energy package" in October 2014, continuing on the "2020 climate and energy package" [1]. The package sets three key targets: cut 40% of greenhouse gas emissions (from 1990 levels), generate at least 27% of energy from renewables and improve the energy efficiency by at least 27% (compared to the projected energy usage). Over the past years, a substantial effort has been put in optimizing the generation and consumption of energy within the European union. The most recent report from 2017 using statistical data from 2015 indicates a reduction of 22.1% greenhouse gas emissions compared to 1990 levels, a 16.7% renewable energy share of gross final energy consumption and a 15.9% energy reduction compared to the hypothetical projection [2]. Although being on track, additional efforts will have to be made to achieve the aforementioned 2020 and 2030 energy targets.

The U.S. Energy Information Administration estimates that in 2016 approximately 279 billion kWh of electricity was used for lighting by the residential and commercial sectors in the United States of America, corresponding to approximately 10% of the total energy consumption of these sectors and

7% of the total electrical consumption in the USA [3]. Concrete data about these proportions within the European Union is not readily available; however, it is reasonable to expect similar ratios. Migrating to LED (Light Emitting Diode) lighting allows considerable energy savings due to its superior efficacy compared to halogen and fluorescent lighting; further improvements are soon expected. The initial cost of purchasing LED lighting has plummeted in recent years, often making it the most economical choice. For those reasons, LED lighting is becoming omnipresent [4].

Light Emitting Diodes and digital electronics in general operate on DC and require convertors when powered by the AC mains [5]. Therefore, the idea has arisen to feed the lighting infrastructure with a low-voltage DC system instead of the mains. This centralized AC to DC conversion approach allows far simpler and more efficient powering of LED lamps, as it avoids an AC to DC converter in every lamp. Simultaneously, this DC system facilitates the integration of digital electronics, simplifying smart lighting control, which improves user comfort and satisfaction and allows for obtaining further energy savings. Additionally, the distribution by means of low-voltage DC reduces the shock hazards that can be induced by the lighting infrastructure.

In this paper, we briefly explain how LED technology has revolutionized the lighting industry. We introduce the basic functioning of LEDs to clearly explain the different ways for powering them. After pinpointing the possible advantages of using a DC grid for feeding the LED lamps, the additional reasons for going back to DC-based electricity distribution are summarized. Benefits and drawbacks of DC-based lighting are further explored. Important factors are ease of maintenance, safety and energy efficiency. For the latter, some measurements are included to give a coarse idea of the energy wasted in the conversion and driver circuitry for AC- and DC-based grids. To achieve a substantial energy saving while keeping or augmenting the user's comfort, the concept of smart lighting is introduced. The paper discusses the different solutions for integrating an intelligent control system in the lighting infrastructure to be able to automatically dim or switch on or off the lamps based on user presence (or user's preferences) and on the availability of daylight scavenging. While presenting the flexibility of DC-based lighting solutions, the paper clearly motivates the design choices taken for the EDISON project [6–8] and introduces the main building blocks of the EDISON smart lighting system. It also introduces the latest efforts to make the EDISON smart lighting solutions interoperate with other (building management) systems.

2. The Success of Light Emitting Diodes for Lighting

The first Light Emitting Diode was documented in 1927 by Oleg Losev, but it is only since the 1950s that research in LEDs accelerated with the increased interest and improvements made in semiconductor technology. Since the 1970s, red LEDs have been commercially available on a large scale; however, their dimness limited their applicability to indicator lamps and seven-segment indicators. The discovery and commercialization of blue LEDs was another breakthrough. This accelerated the development of white LEDs that are based on blue ones but include an yttrium aluminium garnet (YAG) phosphor coating. The coating absorbs part of the blue light and re-emits it, approximating the spectrum of white light. This is done by creating a mix of different colors, each with lower photon energy when compared to blue light.

Thanks to the research in semiconductor and LED technology, one can state that every decade the amount of light produced per LED increases twenty-fold and the cost per lumen decreases ten-fold. So far, this has been historically true and is known as Haitz's law [9], similar to the well-known Moore's law, which is applicable to semiconductors. It is also worth observing that the efficacy of LEDs, being the lumen output per Watt, has drastically increased. Currently commercially available white LEDs achieve 100 lm/W on average, which is well above incandescent and slightly better than fluorescent lighting. A prototype from Cree from 2014 is even able to achieve 303 lm/W [10]. The historical efficacy of LED lamps is available in the analytics tool of [11], which is based on the data aggregated by the LED Lighting Facts program, established by the U.S. Department of Energy. From these data, one can derive that the efficacy of LED lamps has been steadily increasing, as predicted by Haitz's law.

Compared to other light sources, LED lighting achieves very good efficacy and a superior lifetime, which lowers maintenance and operating costs. An extensive set of advantages of LED lighting and a comparison to a variety of other light sources is available in [12]. Furthermore, the environmental impact of LED lighting is less than the impact of compact fluorescent bulbs, currently their main competitor [13].

In recent years, a large increase in LED lighting installations can be observed in Figure 1, taken from the U.S. Department of Energy Revolution...Now report, September 2016 edition [14]. From this chart, it is clear that LED lighting is quickly gaining market share, primarily due to the technology becoming cheaper, but also due to its advantages over other lighting sources.

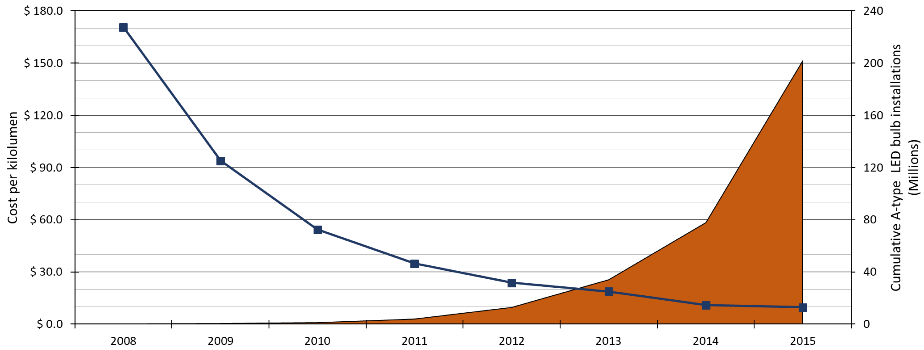

Figure 1. Annual change of LED cost per kilolumen (blue line, left axis) and installations of A-type LED bulbs (orange area, right axis) in the USA. Figure adapted from [14] with permission.

A typical LED lamp consists of two distinct parts: the actual light emitting diodes converting electrical energy into light and an electronic circuit, which is called a LED driver, designed for optimally powering the LEDs. In the following section, we will discuss the type of grids, being AC or DC, for bringing the power to the lamps, and their associated drivers.

3. Powering LEDs

To clarify what a LED needs to produce a stable and controllable amount of light, we briefly illustrate LED powering fundamentals. In most cases, LEDs are fed through the traditional AC-based lighting grids connected to the mains (230 V or 110 V AC). We will have a look at the electronic circuits needed between the grid and the LEDs, typically referred to as LED drivers. For convenience, LED lamps as a whole are often a combination of the actual LEDs and a LED driver. This typical setup is looked at more closely.

Direct current has recently been making a comeback as a potent alternative means for distributing electrical energy and can be beneficial for creating a DC-based lighting grid for LED lamps. To understand the challenges, a comparison is made between the electricity distribution aspects of AC and DC grids. Subsequently, a low-voltage DC lighting infrastructure with DC-based LED drivers is discussed. To highlight some important issues, the energy efficiency of some representative AC- and DC-based LED lighting solutions are evaluated.

3.1. LED Powering Fundamentals

Light Emitting Diodes are a special subset of diodes producing photons when current flows through them. There is a quasi-linear relationship between the current going through a LED, and the brightness of the LED. Indeed, increasing the current results in more electrons and holes recombining and thus more photons being generated. This relationship can be observed in Figure 2a. Because of the almost linear relationship, it is easy to control the light output of a LED lamp by regulating its current. This is particularly interesting for dimming purposes.

The current does not scale linearly with the voltage though, as is the case with all semiconductor devices. In fact, below a certain voltage, almost no current will flow. Above this threshold, a small voltage increment can potentially result in a large current increment. The current–voltage characteristic of a XM-L LED (Cree, Inc., Durham, NC, USA) is depicted in Figure 2b. Furthermore, this nonlinear current–voltage relationship varies with component spread and is temperature dependent. An increase in temperature increases the current for the same voltage, possibly triggering thermal runaway ultimately leading to the destruction of the oversaturated LEDs. Powering LEDs without any current limiting circuitry is therefore strongly discouraged. Series resistors can be added to the circuit to limit the drift of the operating point. Note that such resistors waste energy, resulting in lower efficiency.

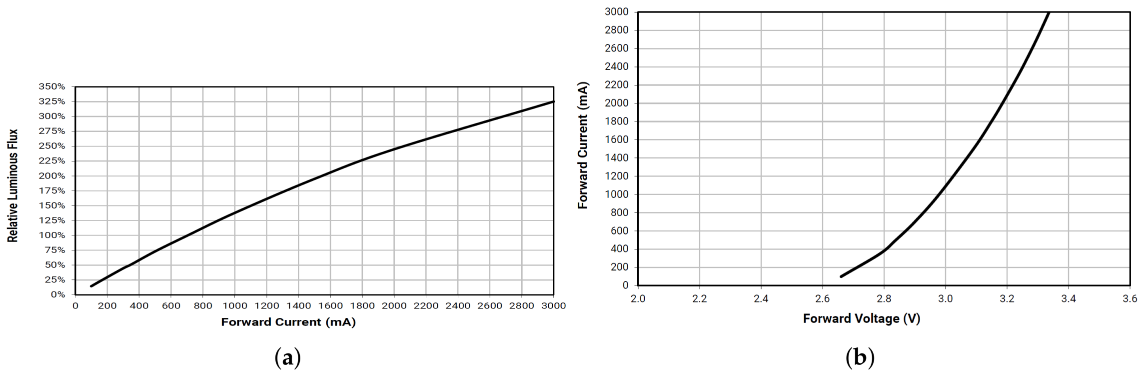

Figure 2. Operating point of a Cree XM-L white LED [15]. Used with permission of Cree, Inc. (**a**) almost linear relationship between LED current and luminous flux; (**b**) current–voltage characteristic. Note the non-zero starting *x*-axis.

3.2. LED Drivers for the Traditional AC-Grid

LED lamps typically consist of two components: the actual light emitting diodes and some power electronics. We highlighted in Section 3.1 why it is recommended to power LEDs by current control, not by voltage control. LED drivers are designed specifically for this purpose. Typically, those drivers are integrated in the LED lamps, although they can also be found as external components. A built-in driver has advantages since the driver is designed specifically for that LED lamp and allows easy installation; a LED bulb can just take the place of a traditional bulb. However, having these electronics integrated often deteriorates the LED lamps' lifetime as they tend to be the weakest point in the chain. Figure 3 shows a typical but simplified design of an AC LED lamp with integrated LED driver.

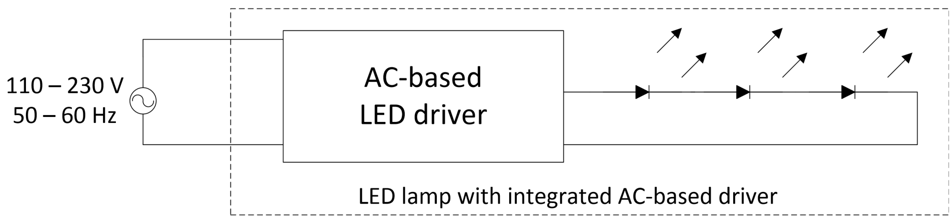

Figure 3. Schematic representation of LED lamp with integrated driver operating on AC.

The goal of an AC-powered LED driver is to produce a stable constant current output from the 50 Hz or 60 Hz AC mains power input. This can be achieved in multiple ways. Several LED driver designs are available, varying in reliability, efficiency, complexity, size, stability and cost. There can also be vast differences regarding dimming support. Dimming will be further clarified in Section 4.2, which treats the control aspect of LED lights.

Some driver designs are very simple and use only passive components. Whereas this is still acceptable for small electrical loads below 25 W, power factor and electromagnetic compatibility (EMC) regulations [16] require complex approaches for more demanding loads. Switched-mode power supplies (SMPS) with power factor correction (PFC) allow high efficiencies while complying to these regulations. These types of converters exist as single-stage, double-stage and even triple-stage designs, and can be galvanically isolated from the mains or directly coupled. Boost-buck is a typical design, depicted in Figure 4 in which the boost stage operates as a PFC, and the buck stage converts down and regulates the LED current. Given the vast amount of possible AC LED driver designs available, it is recommended to consult references [17,18] for an in-depth overview. In [17], a comparison is made between a range of commercial LED driver typologies. Extensive information regarding the design and development of SMPS-based LED drivers is found in [18]. In [19], several SMPS designs are compared and a low cost, high density LED driver is designed. Results on power quality tests are reported in [20].

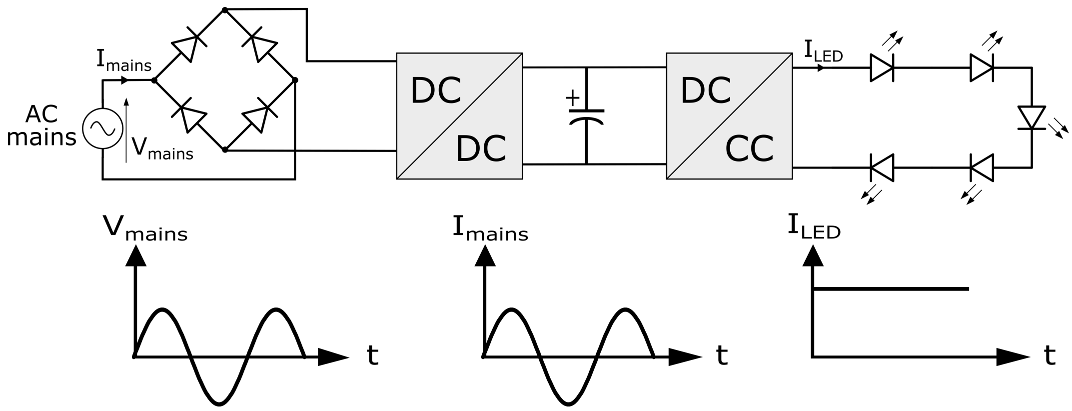

Figure 4. A boost-buck AC LED driver. The bridge rectifier and first DC/DC converter act as a boost stage, functioning as a power factor corrector (PFC). The second stage functions as a constant current source for the LEDs.

The LED driver design specifies the features and compatibility of the entire LED lamp. A LED driver designed to operate on a 230 V 50 Hz mains might not work on a 110 V 60 Hz mains and vice versa, while other designs operate flawlessly within a wide voltage range. In low-cost designs, the output circuit is typically not galvanically isolated from the mains. In this case, extra caution should be taken to properly isolate all metal contacts. Touching these contacts, connected directly to mains, may result in a lethal electrical shock hazards. This potentially dangerous flaw may not only be present in cheap, poorly designed lamps [21]. Issues have also occurred with lamps from renowned brands like Philips. They had to recall 99,000 lamps due to a manufacturing fault possibly leading to a shock risk [22].

3.3. Migrating to DC-Based Distribution

The compatibility of AC-powered LED lamps with the existing infrastructure is convenient but comes at a price. The lamps' safety can be compromised by reckless designs and manufacturing defects, possibly even leading to lethal shocks. Lower efficiencies are noticeable as compared to directly powering with DC. The extra components needed for the AC conversion result in additional points of failure, possibly reducing the lifetime. Additionally bad power factors and electromagnetic interference can pollute the mains.

Given LEDs' DC nature, these issues can be avoided or at least be reduced by migrating to a DC-based lighting infrastructure. Converting the existing lighting infrastructure to DC can appear radical and complex at first sight. In many buildings in Europe, the electric circuitry for lighting and appliances are strictly separated. When this is the case, retrofitting the lighting circuit to DC-based distribution is quite easily achieved. Obviously, the same result is achieved when deploying a completely new electrical infrastructure dedicated to lighting.

Indeed, going back to DC is not a hollow phrase today. Direct current is regaining popularity. Let us first examine the reasons for the resurgence of direct current and the possible disadvantages. In Section 3.4, the choices made for the EDISON DC-based lighting infrastructure solution shall be motivated.

3.3.1. The Comeback of Direct Current

Direct current has been making a 21st century comeback [23] with the advances in semiconductor technologies throughout the 20th century and the continuing migration towards digital electronics. In fact, the vast majority of electronic devices these days are internally powered by DC, whether a computer, a television, a smartphone, an LED lamp, etc. Digital electronics have become so powerful and cheap that they are ubiquitous in our daily life. The basic building block of digital electronics is the transistor that is powered by DC. As such, digital devices require the necessary conversion electronics to transform the AC mains into a low voltage DC.

Switched-Mode power supplies provide a variety of electronic conversions, ranging from AC/DC, DC/DC, DC/AC, and even AC/AC. A survey of this topic is available in [24]. These power supplies operate by rapidly modulating an electrical signal and are typically smaller, lighter and cheaper than their transformer-based counterparts operating at grid frequency, while achieving higher efficiencies. Given these advantages, these days the vast majority of electronic devices are powered by SMPSs. In fact, solid-state power electronics are even becoming increasingly interesting for AC/AC conversions [25], a field that has long been dominated by transformers and played an important role in winning the "war of currents".

Direct current also has clear advantages related to the shift towards green energy. Photovoltaic panels, being a semiconductor technology, generate direct current electricity from (sun)light. Conventionally, this DC electricity is immediately transformed into AC, synchronized with the mains by an inverter, before it is used locally or pushed on the mains. DC to AC conversion efficiencies of 90% are achievable; however, it is useless and wasteful when, at the very end, this energy is consumed as DC. Windmills typically generate alternating current but seldom synchronized by nature with the mains frequency because of a varying wind speed. Currently, the most popular windmill type uses double fed induction generators, allowing net synchronization within a limited variable speed range. However, this type of generator requires frequent maintenance and newer windmill designs are focused towards simpler generators with electronic power converters for synchronization [26]; using SMPS' AC/AC converters with intermediate DC. From this, we can conclude that both wind and photovoltaic energy sources would perform more efficiently on DC grids.

Another property of green electricity generation is that it is irregular by nature: the wind speed is not constant and neither is sunshine on a partially clouded day. This is an issue because mains electricity generation and consumption have to be precisely balanced. Maintaining stability of the mains, or of local microgrids or pools of collaborating microgrids [27], can be aided by temporarily storing excess energy during surpluses—for instance, by temporarily storing it in batteries or large capacitors. Storing electricity can also be financially beneficial for owners of PV systems in case there are lower rates for injecting in the mains than for consuming from the mains. A prime example of a commercially available battery for this purpose is the Tesla PowerWall (Tesla, Inc., Palo Alto, CA, USA) [28]. The electrical charge stored in batteries and capacitors is in the form of direct current, once again favoring DC distribution to reduce conversion losses.

However, direct current can create some issues. Switches, relays, circuit breakers, etc. that physically interrupt the current flow must be more robust when using DC, as will be further explained in Section 4.1. The main concern with migrating the complete electrical infrastructure in buildings to DC is that the convention is a 230 V 50 Hz or 110 V 60 Hz AC mains and many devices are simply not designed to operate on another electric power source. In the near future, we will be seeing more and more cases in which both AC and typically a low-voltage DC distribution system work side-by-side [29–31]. Complete DC homes and offices are already being prototyped and could also become commonplace in the quest to optimize efficiencies [32,33].

3.3.2. Distribution and Operating Voltages

Let us have a look at the current situation. The typical mains voltage for consumers is 230 V_{AC} or 110 V_{AC}. Being a suitable voltage for powering homes and companies, to transport or distribute large amounts of electrical energy over longer distances requires higher voltage levels, which range in Belgium up to 380 kV_{AC}. When it comes to distributing electricity, two key losses must be taken into account: cable losses and transformation losses.

Cable losses are the electrical losses originating from the electrical resistance of the cable and depend on its length, area, and conductive material. Resistive cable power losses increase exponentially with current and furthermore lead to a voltage drop, expressed by Formulas (1) and (2) respectively, where I denotes the current, ρ denotes the material's resistivity (1.68×10^{-8} Ωm for copper), L is the cable length, and A is the cross section of the cable. From these formulas, it is clear that the current should be limited in order to restrict losses. Additionally, a voltage drop of 20 V on a 230 V system represents a drop of 8.70%, whereas that same 20 V drop is only a 0.13% loss on a 15 kV system. As such, transporting electrical energy on higher voltages is far more interesting:

$$P_{cable} = I^2 \frac{\rho L}{A}, \tag{1}$$

$$V_{cable} = I \frac{\rho L}{A}. \tag{2}$$

When developing a DC-based lighting infrastructure, the same trade-off must be made. On one hand, higher voltages result in fewer distribution losses. On the other hand, lower voltages simplify powering semiconductor devices like LEDs and micro-controllers, and have additional benefits such as improved safety and reduced risk of shock hazards.

Extra-low voltages (ELV) are a range of voltages carrying a low risk of dangerous electrical shock. IEC standard 60364 [34] defines voltages below 50 V_{AC} root mean square (RMS) and 120 V_{DC} between both conductors, and between conductor and earth, as ELV. Further subdivisions are safety extra low voltage (SELV) and protected extra low voltage (PELV), ensuring ELV under single-fault conditions including (SELV), or excluding (PELV), earth faults in other circuits. These systems are considered very safe for use under normal conditions. Common ELV appliances are, for instance, laptop and smartphone chargers. A key advantage of ELV compliance is that an earthing connection is no longer required for ensuring safety. This is particularly interesting as electrical cabling in buildings typically consists of three wires: neutral, phase, and earth; the latter could now technically be used for different purposes.

3.4. DC-Based LED Lighting Infrastructure and Associated LED Drivers

Some investigation is needed before deploying a DC-based lighting infrastructure. Obviously, it breaks the convention of distributing 230 V_{AC} or 110 V_{AC} indoors and should only be applied when lighting circuits and appliances are strictly separated. Luckily, this is the case in many buildings and is not an issue when installing new electrical systems. Needless to say, all the devices on these DC-based lighting circuits have to be compliant with the distributed DC voltage. AC-powered LED lamps that were already in service on these circuits are very likely not compatible and have to be modified or replaced.

The primary design choice when developing a DC-based lighting system is the operating voltage. In [35], a system has been presented that operates on 24 V_{DC}. In [36], a "low voltage DC" is used without specifically mentioning the operating voltage. The scalability of these systems can be an issue because of the maximum power that can be distributed. The currents required for powering a noteworthy amount of LED lamps result in significant cable losses and voltage drops. This not only voids the efficiency gains made by switching to DC, it might even exceed the cables rated current. These issues would not occur in the lighting system presented in [33], which has been integrated within the building's 380 V DC grid.

Having a sufficiently high voltage is preferred, but from an economical point of view, it is also important to make the design choice according to the commercially available DC power supplies and LED drivers. Given these parameters, for the EDISON DC-based lighting system, the operating voltage has been chosen on 48 V_{DC}. It is sufficiently high for the vast majority of lighting applications, has a variety of available cost-efficient DC-based LED drivers and is well within the extra-low voltage specification introduced in Section 3.3.2.

The 48 V_{DC} is provided by one or multiple high-efficiency AC/DC power supplies with active power factor correction (PFC). Efficiencies of up to 96% are achievable under ideal circumstances from commercially available products [37]. Secondary power supplies can be used as a backup, automatically taking over in case of failure.

The DC infrastructure requires compatible LED drivers. These can be integrated within the LED lamps themselves, or as external devices. In the latter case, the LED lamp is a "passive" device consisting of only LEDs without any additional electronics. The advantage of having external LED drivers is that both replacement costs and electronic waste are reduced in case of failure. Pay attention to the fact that the operating current and voltage range of the LED driver and "passive" LED lamp must be compatible. A simplified schematic of the DC-based lighting solution with "passive" LED lamps and external drivers is illustrated in Figure 5.

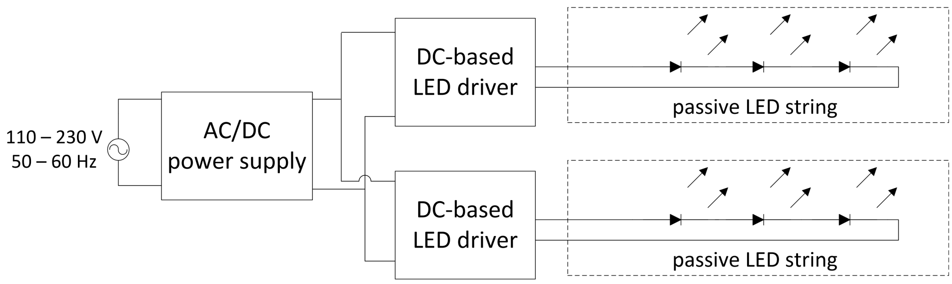

Figure 5. LED lamps with external drivers operating on a DC infrastructure.

3.5. Measuring and Comparing AC- and DC-Based LED Lighting Solutions

In the following tests, three AC-powered LED drivers are compared with a combination of three DC-powered LED drivers and two DC power supplies.

These measurements are performed with 2 Metrix PX-110 RMS power meters (Metrix Electronics Ltd., Bramley, UK). This allows for measuring the input and output power consumption simultaneously. This is important, as the power consumption changes over time due to heating of the components. Because of this, several measurements per setup have been performed at different times. For reliability purposes of the measurements, the power meters have been tested on accuracy before starting these experiments. No observable deviations have been found between the power meters.

Three ordinary and affordable AC-powered LED drivers from different brands are tested on the same 1000 mA, 40 W LED panel. The LED drivers are chosen in function of this LED panel's current rating. However, do note that the tested Osram LED driver (Osram Licht AG, Munich, Germany) is rated at 1050 mA, rather than 1000 mA. The measurement results and derived efficiencies are available in Table 1.

Table 1. Operating current, power and efficiency results of the AC-powered LED drivers.

AC-Powered LED Drivers	Current (A)	Power (W)	Efficiency (%)
Osram OT FIT 50/220-240/1A0 CS	1.06	42.7	85.2
Mean Well NPF-40D-42	0.96	37.8	86.6
XP Power DLE45PS48	0.99	39.2	87.1

The efficiency of the DC-based LED solutions depends on two factors: the efficiency of the DC-based LED drivers, and the efficiency of the DC power supplies. These measurements have been performed individually to provide a clear insight into the contributions of each part. Three DC-powered LED drivers are tested on the same LED panel as used previously. Of those, two LED drivers are commercially available. The third LED driver is a generic LED driver that was shipped with the LED panel. The results are available in Table 2. Do note that, although all three LED drivers are rated at 1000 mA output current, their actual output current levels vary considerably. Whereas this does not appear to have a significant impact on efficiency, it does effect the luminous flux output and can impact the LED panel's lifetime.

Table 2. Operating current, power and efficiency results of the DC-powered LED drivers.

DC-Powered LED Drivers	Current (A)	Power (W)	Efficiency (%)
XP Power LDU4860S1000	0.90	35.2	95.1
Generic LED driver	1.07	42.8	96.3
Mean Well LDD-1000H	0.97	38.3	96.9

The results in Table 2 indicate that the tested DC-powered LED drivers are on average approximately 10% more efficient than their tested AC-powered competitors. However, one has to also consider the conversion losses experienced when converting AC mains into the used 48 V_{DC}. For this, two 48 V_{DC} power supply units (PSUs) are tested over their output power range on a resistive load bank to map their efficiencies relative to the load. A 600 W Mean Well HEP-600-48 high efficiency PSU (Mean Well Enterprises CO., LTD., New Taipei, Taiwan) and a 480 W XP Power DNR480 PSU (XP Power, Singapore) with ordinary efficiency are tested. Their results are plotted in Figure 6. From this data, one can observe that the tested PSUs perform most efficiently near their rated output power and perform significantly inefficient under restricted loads. Near their rated power, the DNR480 PSU achieves up to 88.5% efficiency and the HEP-600-48 achieves up to 94.5% efficiency.

The efficiency of the complete DC-based LED lighting system is obtained by combining the efficiencies of the DC-based LED drivers and the PSUs. A comparison of the total efficiency of a system with either an XP power DNR480 or Mean Well HEP-600-48 power supply, at a variable load, and combined with Mean Well LDD-1000H LED drivers (Mean Well Enterprises CO., LTD., New Taipei, Taiwan), is provided in Table 3.

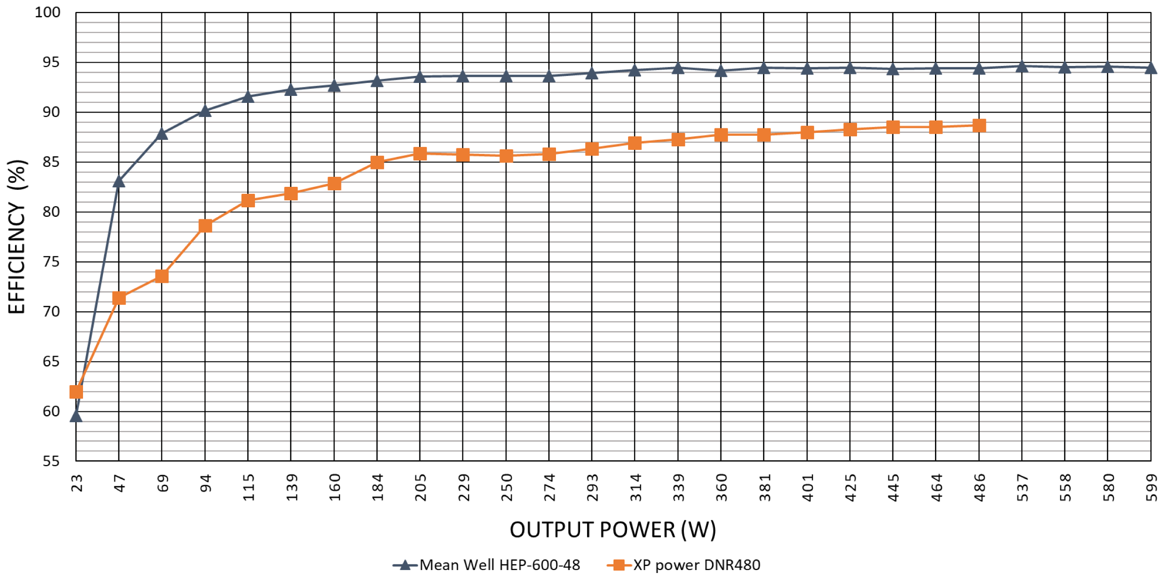

Figure 6. Efficiency measurements in function of output power for two 48 V_{DC} power supplies using a resistive load bank.

Table 3. Total system efficiency of a DC-based LED lighting system using Mean Well LDD-1000H LED drivers. The efficiency depends on the choice of power supply unit (PSU) and its load compared to its rated capacity.

PSU Load	XP Power DNR480	Mean Well HEP-600-48
20%	76.2%	88.8%
40%	82.8%	90.8%
60%	83.6%	91.3%
80%	85.1%	91.5%
100%	86.0%	91.6%

From these results, one can conclude that, from an energy efficiency point of view, it can indeed be beneficial to migrate to a DC-based LED lighting infrastructure. However, some things have to be taken into consideration. The choice of the DC power supply has a non negligible influence on the total system's efficiency. Additionally, the capacity of the power supply has to be chosen with respect to the load, as having a light load compared to the rated capacity harms efficiency.

3.6. LED Powering Conclusions

The rise of direct current is easy to explain. It is simpler and more efficient to power DC-based technologies, which are omnipresent in our daily lives. Now that LED lighting is becoming the de-facto standard lighting source, the deployment of a low-voltage indoor DC-grid, at least for lighting, is beneficial. The experiments carried out in Section 3.5 indeed indicate that DC-powered LED lighting can be more efficient and cost-effective under the correct conditions. Furthermore, low-voltage DC grids have the additional benefit of improved safety.

4. Controlling LED Lighting

In this section, we will review ways to control LED lighting, generally applicable or specifically for an AC or DC solution. We begin with basic interaction, which is the manual control of the LED lights to their on and off states using switches. Subsequently, we have a look at the dimming capabilities of both the AC and the DC solution.

Automation is playing an increasingly prominent role in the quest to optimize systems. Smart lighting allows more punctual control of the lighting infrastructure resulting in further energy savings and increased user satisfaction. The basic building blocks of smart lighting solutions are introduced and their applicability for DC will be discussed. A dedicated Section 5 will further elaborate on the myriad of choices for organizing communication.

4.1. Basic On/Off Lighting Interaction

Manually controlling the lights by means of interrupting the current flow is the most basic form of interacting with them. This method is self-explanatory and should not need and further explanation—or does it?

Turning off the lights in a DC-based lighting system might appear trivial, but, unfortunately, it is not. An arc occurs when disrupting a sufficiently large current. This phenomenon happens both in AC and DC environments. In AC environments, there are zero-crossings occurring twice per period in which no current flows, which can stop the arc. This is not the case in DC environments, so arcing will not be automatically interrupted. Switching devices, whether lighting switches or relays, need to be specifically dimensioned to cope with the given DC voltages and currents; otherwise, arcing might be sustained and excessive wear will occur in the switching contacts. Looking at the specifications of switches and relays, the maximum switching DC voltages are far lower than their AC counterparts.

When overhauling the lighting infrastructure to DC, it is the perfect moment to upgrade from the classical lighting switches to their electronic variant. After all, this DC infrastructure suits electronics. Transistors are semiconductor devices just like LEDs and are ideal for electronically controlling DC currents. Power metal-oxide-semiconductor field-effect transistors (MOSFETs) with low resistance are a suitable electronical replacement for lighting switches. Although the gate is typically being electronically controlled, it is still possible to do this manually with mechanical switches like lighting switches. Interrupting the signal to the gate is easy, as the gate hardly draws any current. An example circuit involving an N-channel metal-oxide-semiconductor (NMOS) is given in Figure 7. The flyback diode in parallel with the LED drivers protects the MOSFET from voltage spikes caused when interrupting inductive loads.

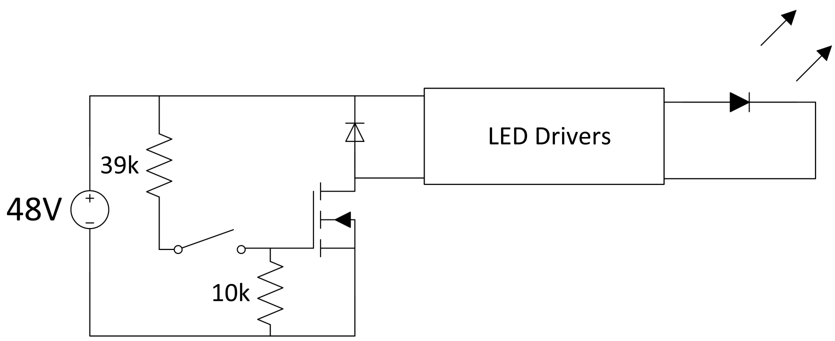

Figure 7. Controlling the DC current flow with a metal-oxide-semiconductor field-effect transistor.

4.2. Dimming

Having the possibility to precisely control the lighting output is an interesting feature. Dimming is frequently used to create different ambiances depending on the mindset and activity. It can also realise significant energy savings. Given the almost linear equation between luminous flux and current flowing through a LED, as mentioned in Section 3.1, LED lighting can potentially lend itself perfectly to dimming control. It is the task of the LED driver to regulate the current flow through the LEDs, hence, when supported, dimming is realized by altering the operating point of the LED driver.

Traditional dimming in an AC lighting infrastructure is realized by cutting off part of the AC voltage waveform, lowering the average voltage and power. This works well for resistive loads like incandescent lamps but is harder to achieve for LED lighting, as typical LED driver designs try to keep the output current going to the LEDs constant [38]. Some types of LED drivers have additional electronics for detecting those voltage waveform manipulations and can be dimmed by conventional AC dimmers. Others allow dimming by having separate dimming control pins. The very basic LED drivers are fixed and will not dim at all, start flickering or might even be damaged when being controlled by AC-based light conventional dimmers.

External LED drivers, both AC- and DC-powered, can be equipped with dimming control pins featuring one or multiple control methods. These methods can be diverse and depend on the LED driver in question. Typical methods are controlled through changing the resistance value of a potentiometer, controlled through a 0–10 V signal, and controlled through a pulse-width modulated (PWM) signal. More complex LED drivers can also support digital addressable lighting interface (DALI) or similar networking technologies for remotely controlling the lighting.

PWM is the de-facto standard when it comes to simple and robust digital modulation techniques. By only providing current to the LEDs during the active part of the PWM duty cycle, it is possible to dim a LED lamp. The Mean Well LDD-H series are cost-effective external DC-powered LED drivers that allow PWM dimming control [39]. Do note that some considerations must be taken into account when selecting the PWM actuation frequency. Below approximately 100 Hz flickering might be detected by the human eyes.

Now that it is possible to precisely control the LED lighting infrastructure, it is a good idea to automate this system.

4.3. Automatic Control for Enabling Smart Lighting

Energy savings can be achieved by automating the lighting system to reduce the light output, or turning off the light all together, whenever possible. Typical situations in which the light output can be reduced, are whenever nobody is present, or when there is already sufficient daylight.

Smart lighting exists in a variety of cases with different features and complexities. An elementary case of automated lighting control would be a flood lamp with motion and illuminance sensor that automatically turns on at night for a certain duration whenever movement is detected. Although being very basic, such a system contains many of the essential features of a smart lighting system.

Full-fledged smart lighting systems could be customizable based on the time of the day and the users' preferences or could be further integrated within a building automation or heating, ventilation and air conditioning (HVAC) system. For instance, the lighting systems' presence sensors information could be used within the HVAC system to detect when a room is unoccupied, such that it can be lowered or deactivated. The lamps could be programmed to gradually light up or darken and can be actuated to keep a nearly fixed illuminance level throughout the day with changing natural light levels. Smart lighting could be used to detect whenever a certain LED lamp requires maintenance or even automatically compensate for LED degradation. Special types of LED lamps allow changing their color temperature between yellowish and blueish and can mimic the sunlight cycle throughout the day. These systems may improve the day-night rhythm and are particularly interesting in Nordic countries during winter time [40]. Other smart lighting systems can modify their color altogether between several shades, thereby creating different ambiances. Smart lighting is also becoming increasingly popular in greenhouse agriculture, as the precisely controllable lighting environment allows better crop yields [41,42].

The LED-based smart lighting infrastructure could furthermore be used for Li-Fi (Light Fidelity) [43], an optical alternative to WiFi. It operates by rapidly modulating the LED lighting, far quicker than the human eye can notice, to transfer data and can be integrated within the building's LED lighting infrastructure. This modulation even works when the LED lights are almost completely dimmed and appear to be off for the human eye. Li-Fi is a promising technology for achieving wireless and secure high-bandwidth communication, but is currently still in its infancy.

Let us briefly look at the essential building blocks of a smart lighting system, and demonstrate how the DC-infrastructure facilitates the design and deployment of these components. Sensing, processing and actuating make up the core of the control system and are typically combined with a form of communication. A simplified schematic is provided in Figure 8. Having inter-node communication allows direct sharing of sensor information with actuators, whereas communication with a gateway allows remote control, monitoring and processing. These nodes can even be full-fledged Internet of Things (IoT) or Web of Things (WoT) devices, easily reachable from any Internet Protocol (IP)-based device and the latter also from any internet browser [44–47]. These technologies are frequently combined with cloud computing for achieving far more powerful processing and data mining, although being hindered by networking delays for time-critical actions. Fog computing [48] and edge computing [49] operate at the local level, allowing latency reductions down to near real-time levels.

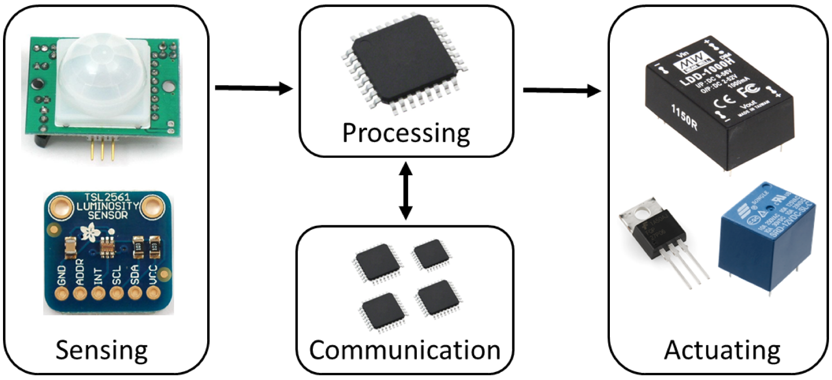

Figure 8. Simplification of smart lighting essentials: sensing, processing, actuating and communication.

4.3.1. Sensing the Environment

Smart lighting relies of the environmental parameters provided by one or multiple sensors. Motion/presence detection sensors are typically used for detecting whether there is someone present in the room. Illuminance sensors detect whether there is sufficient daylight present so that the artificial lighting might be deactivated or dimmed. These sensors are stand-alone devices or integrated within the lighting fixtures. However, it is even possible to turn LED luminaires themselves into sensors by deploying customized drivers to measure the photoelectric effect [50]; in this way, it is possible to detect occupancy without explicitly requiring dedicated sensors. Additionally, imaging cameras can be used in the quest to achieve optimal lighting quality [51].

Interconnected smart lighting solutions can benefit from having additional sensors in place to detect temperature, humidity, CO_2, etc. whenever combined with a HVAC system. Other interesting measurable parameters are the condition of the LED lamp and its power consumption.

Note that small electronic devices, such as sensors, could benefit from a DC-based lighting infrastructure, as explained in Section 3.3.1.

4.3.2. Actuating the LED Luminaries

The energy savings gained from a smart lighting system originate from actuating the LED lamps. Actuation can range from simply on/off control by electronically controllable switches, being relays and transistors, to precise dimming control if supported by the LED driver. These actuation methods have been previously clarified in Sections 4.1 and 4.2, respectively. PWM-based dimming control is the preferred actuation control method given its omnipresence in dimmable LED drivers. Additionally, a PWM-based control signal is easily generated by the local control unit.

Based on the available budget and desired functionalities, actuation can occur in a coarse-grained or fine-grained manner. In the former, actuation takes place per group of LED luminaries. This requires less resources and is therefore cheaper but somewhat limits control. In the latter, actuation occurs on each LED luminary individually. This requires additional components and thus a greater initial investment; however, it allows more precise control and potential energy savings. All non-necessary fixtures, for instance luminaries close to the windows, can often be disabled during the daytime, whereas luminaries further away from the windows might still need to be powered to achieve suitable luminance levels. Having fine-grained control furthermore allows more detailed customization based on the users' preferences and makes them feel more in control.

4.3.3. Controlling and Processing

A control unit is responsible for aggregating sensor information and actuating one or multiple LED lamps by a PWM or by discrete on/off signal. Basic processing of sensor information and controlling actuators requires few resources such that simple micro-controllers are satisfactory and cost-efficient. More powerful processing can be taken care of by the fog or cloud, in case a communication interface is present. There, additional features such as keeping track of the number of operating hours, having customizable lighting preferences, etc. can be provided.

Note that small electronic devices, such as micro-controllers, could benefit from a DC-based lighting infrastructure, as explained in Section 3.3.1.

4.3.4. Communication

The potential of smart lighting can only be unlocked when devices are able to communicate. The bandwidth requirements of a regular smart lighting system that does not consist of complex sensors such as imaging cameras are low. Latency, however, is important and should be kept to a minimum to have a performant lighting control system. Cloud-based processing should therefore be restricted to non-time-critical matters.

Given the multitude of available communication infrastructure and its importance for smart lighting, communication is more thoroughly handled within Section 5.

5. Communication Infrastructure

Realising successful information exchange depends on a combination of multiple communication aspects. Connectivity allows exchanging information between nodes within a network and provides the basis for communication. While allowing data to be exchanged between nodes within the network, it does not define the meaning of the exchanged content. This is tackled by interoperability.

In the following sections, the connectivity aspect required for a smart lighting system are described for multiple communication technologies. Afterwards, when it is possible to communicate, a solution is provided for enabling interoperability.

5.1. Realizing Connectivity

Connected devices can exchange data packets between them. For realising this, wired or wireless communication technologies can be deployed. Wires can be pulled for the control packets, or those control signals can use the existing wires used for powering the lamps. The wired infrastructure can be combined with a variety of wireless solutions. We indicate their applicability within an AC- or DC-based smart lighting system.

5.1.1. Dedicated Communication Wiring

Having communication with separate wiring for powering and communication is the traditional solution. It allows efficient distribution of electricity over the electrical wiring and offers a separate, reliable, low-noise communication environment. Given that it is a separate communication channel, it is applicable to both AC and DC lighting infrastructures.

RS-485 and CAN-bus (Controller Area Network) are popular serial communication standards that can be used in building and industrial applications—the latter being the better choice because it is far more recent, more robust, allows more nodes on the bus and has a CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) with priority-based access. It is primarily developed for automotive applications but works just as well in industrial applications and building automation.

Twisted-pair Ethernet cable can also be an interesting choice because it is omnipresent and allows high bandwidths suiting more powerful devices such as IP cameras. Furthermore, it can be used as a backbone for Li-Fi communication. However, as it is a star-based system, instead of a bus, it requires separate cables for each device.

The major downside of this type of solutions is that having two, or more, separate cables can be tedious when installing new lighting infrastructure and might be impossible when retrofitting. More easily deployable alternatives exist.

5.1.2. Wireless Communication

Wireless communication is becoming increasingly more popular for smart devices as it is easily deployable. Because of its lack of wiring, it is applicable both to AC and DC lighting infrastructures. Common wireless communications technologies range from laptops, smartphones and tablets communicating over IEEE 802.11 WiFi, to interaction with smart watches, wireless speakers and hands-free calling over IEEE 802.15.1 Bluetooth. However, these popular communication technologies have some drawbacks for smart lighting: WiFi is too resource-intensive and Bluetooth until very recently only had a star topology with very restricted range (10 m) and furthermore only allowing a limited number of active connections.

However, the effectiveness of Bluetooth for smart appliance purposes has changed very recently as the Bluetooth Special Interests Group has released the Bluetooth mesh standard [52] in July 2017. Given this mesh networking ability, and its wide support by consumer goods, it is expected to become a major player for connecting smart devices. Currently though, the IEEE 802.15.4 based ZigBee protocol, operating in the same ISM (industrial, scientific and medical) 2.4 GHz radio band and developed for lightweight mesh communications with a small protocol stack, is the most common solution and is demonstrated in many smart lighting projects [35,53–55]. The popular commercially available Philips Hue smart ecosystem also uses the Zigbee protocol stack for communication [56].

It is possible to create full-fledged Internet of Things (IoT) devices on top of the IEEE 802.15.4 medium access control (MAC) and physical layer, by using the Internet Engineering Task Force (IETF), Internet Protocol based standards for small autonomous devices [57,58]. Popular platforms like the Zolertia Z1 and RE-Mote support these IETF based stacks and are actively used for research purposes. Multiple lightweight operating systems support these platforms and facilitate setting up IoT devices; the most popular being Contiki and TinyOS. Communicating with these devices occurs through the Internet Protocol, making it very easy to integrate them within existing networking infrastructure and facilitating the retrieval of sensor information and organization of the remote control of luminaries.

The main advantage of wireless communication is that no wires need to be pulled. Battery powered wireless sensors are particularly interesting as they are mobile and can be flexibly installed in many locations. However, one can expect that the smart lighting infrastructure is fixed in space and powered by cables anyhow, so why use wireless communication? It should be noted that the ISM 2.4 GHz frequency band is already heavily saturated by WiFi and Bluetooth, causing massive interference [59]. Furthermore wireless communication can be easily intercepted and even hacked without having physical access. A worm attack has been demonstrated on Philips Hue lamps in [60].

5.1.3. Power Line Communication

Several power line communication (PLC) standards exist and support the use of digital communication over a two wire AC or DC powered line. A well known and basic PLC standard for AC lines is the Industrial Power Line standard X10. This standard implements a low-bitrate protocol that encodes one bit at every zero crossing of the 50 or 60 Hz AC power signal. This very basic protocol has the advantage of being low cost and widely available. However, its extremely low bitrate limits its usability for contemporary smart lighting systems in large buildings with individually addressed sensors and actuators. Its lack of providing a trustable and secure communication channel has led to the creation of new standards for high as well as narrow bandwidth secure power line communication.

High throughput PLC, which is developed by theHomePlug Alliance and is standardized as the IEEE 1901 Powerline standard, is mainly focusing on broadband applications like video, multimedia and Ethernet over PLC. For smart lighting purposes, where communication should span over large areas, chipsets for medium-bitrate applications have been pushed by major chip-manufacturers like Texas Instruments (Dallas, TX, USA), Philips (Amsterdam, The Netherlands), and ST Microelectronics (Geneva, Switzerland). Those dedicated chipsets contain a full PLC transceiver in combination with a local processor and some memory for application development. Those chipsets are now becoming an enabler for fine-grained light control. An alternative to the use of a dedicated chipset is the use of a micro-controller with a separate analog PLC front-end [61]. This approach is a bit more challenging, but might lead to low cost implementations, if the basic smart-lamp already contains a microcontroller with enough computing capacity.

Some standards have been implemented that describe the signaling and modulation requirements for narrow band PLC. Many chip sets that are compliant to the standard are now available at a cheaper cost than competing wireless radio frequency (RF) technologies. Due to their cost advantage, and integrated computation ability, the narrow-band PLC chips are becoming more and more a convenient choice for smart lighting applications, where fine grain light control is required.

Multiple modulation schemes for PLC communication have been proposed ranging from simple ON-OFF Keying methods to more robust techniques like Spread Frequency Shift Keying (S-FSK) and Orthogonal Frequency Division Multiplexing (OFDM). The latter communication methods have been included in the current PLC standards and are supported by the most PLC-modems. Table 4 details some low-bitrate PLC standards that are typically used for smart grid applications.

Table 4. Overview of low bitrate Power Line Communication (PLC) standards.

Standard	Modulation Scheme	Occupied Band	Data Rate
G1	S-FSK	60–76 kHz	1.2–2.4 kbps
Prime	OFDM	42–90 kHz	21–128 kbps
ERDF G3	OFDM	35–90 kHz	5.6–45 kbps
P1901.2a (2015)	OFDM	35–450 kHz	34–234 kbps

In order to be able to use a specific PLC standard on AC-lines in a certain region, regions' signalling standards to avoid interference has to follow. In Europe, this would be the CENELEC EN 50065-1 standard [62]. Data-intrusion causing interference onto the mains of neighboring buildings is a potential hazard, which might influence the overall reliability of PLC-systems on AC-grids, if the system is not carefully following the standards.

So far, no specific PLC requirements have been posed for DC-grids. In the most cases, DC-grids are self-contained grids, with a centralized AC/DC conversion. The DC grid is nicely isolated from the AC-grid, through one or even multiple transformers of the AC/DC power converters. In case of smart lighting systems that are based on a DC-grid, it is feasible to use simple but robust proprietary low-bitrate solutions like the PLC-Lite protocol stack of Texas Instruments.

Since the DC-grid is less noisy and essentially isolated from the AC-grid, the hardware cost is typically lower than AC-grid PLC solutions. For interoperability at the physical layer, one of the standard communication protocols can be implemented. However, if the system does not require all the complex features of standards like G3 or Prime, only a subset or even a completely proprietary communication stack can be considered. On the application layer, specific tailored solutions for smart lighting can be designed.

Due to these simplified design constraints, it is possible to combine the signal processing and communication protocol on the same processing unit that contains also the main steering application for the smart light control.

5.1.4. Power over Ethernet (PoE)

Using the Ethernet infrastructure for lighting can be an interesting option because it is so omnipresent. While primarily being focused on achieving reliable and high-bandwidth communications, multiple standards exist and more are in the making for distributing DC power on top of the Ethernet cables. They are denoted as "Power over Ethernet (PoE)" solutions. Their ease of use and deployment facilitates the introduction of M2M (Machine to Machine) devices within buildings, and can also be used for smart lighting as studied in [63]. In "The Edge" office building in Amsterdam, a fully automated building has been created in which the LED-based lighting infrastructure is controlled and powered by PoE [64], although restrictions regarding power must be respected.

Several types of powering modes and devices exist. The IEEE 802.3at-2009 PoE specification allows up to 12.95 W for type 1 and 25.5 W for type 2, whereas the upcoming IEEE 802.3bt specification should allow up to 51–60 W for type 3 and 71–90 W for type 4 [65]. This means that even with the most powerful specification only 90 W can be distributed, heavily restricting the number of LEDs that can be powered. Each separate LED luminary should have its own Ethernet cable, rapidly making cabling a difficult and bothersome task. Furthermore, PoE switching equipment is still in its infancy, making it an expensive choice.

5.1.5. EDISON PowerLAN

When migrating to a SELV-compliant (see Section 3.3.2) DC-infrastructure for LED lighting, only two wires are needed. The third available wire in the electrical cabling, originally used for earthing purposes, is no longer required given the SELV properties, and can be used for communication. This is the case in the EDISON DC-based lighting infrastructure, and is named the EDISON PowerLAN.

The EDISON PowerLAN uses the electrical cabling infrastructure both for power distribution and communication. This allows maintaining the existing electrical cabling when refurbishing the lighting infrastructure, at least when the experienced cable losses and voltage drop are not exceeded by switching to a lower distribution voltage. A visual representation of the use of each of the three electrical wires in the EDISON PowerLAN is available in Figure 9.

Communication occurs on one wire with a common return wire, facilitating a single-ended signaling style. Contrary to differential signaling, single-ended signaling is far less robust to noise. Additionally, a voltage shift in the common return wire, caused by the current flowing to power the LED luminaries, may cause incorrectly interpreted communication states. These issues can be countered by using sufficiently high voltages on the data line combined with low baudrates.

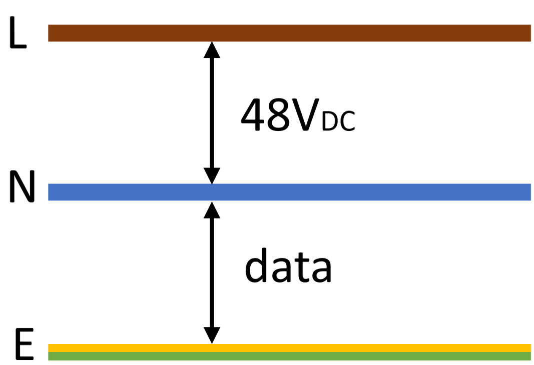

Figure 9. Powering and communication over the 3-wire electrical cabling.

A master/slave model is used given the simplicity of the communication infrastructure. As such the Modbus RTU (Remote Terminal Unit) application protocol is an ideal choice given its simplicity and its industrial acceptance. The means of communication and Modbus application protocol are easily supported by simple microcontrollers, making it a very budget-friendly solution when only requiring low-bandwidth communications. The Modbus master aggregates information by periodically polling each slave node and can update the status of each lighting fixture.

Note that while being technically safe and allowed by the CENELEC (European Committee for Electrotechnical Standardization) umbrella organization, national legislation may be more strict or dissuasive, making this solution impossible. This is, for instance, the case in Belgium where the yellow-green earthing conductor cannot be used as an active conductor [66].

5.2. Realizing Interoperability

Currently, the fourth industrial revolution is developing on top of the digital revolution in which Machine-to-Machine (M2M) communication is becoming ever more prominent. The intelligent lighting infrastructure can be extended to support M2M and Internet of Things (IoT) communication whenever an IP-based protocol or application gateway is being used.

Providing connectivity between devices is an achievement discussed in Section 5. For multiple systems, whether from different sectors or different manufacturers or standards, being able to understand each other is another challenge.

Interoperability allows communication between heterogeneous systems and can be achieved on multiple levels. Technical interoperability allows systems to exchange packets with each other and typically goes up to the networking layer. It is called connectivity within the telecommunication world. Syntactic interoperability specifies the communication protocol and data format being used. This allows exchanging information but does not necessarily mean that this information is interpreted in the same way across heterogenous nodes; the model of a certain sensor in node A might differ from the model in node B leading to misinterpretation. Semantic interoperability solves this by ensuring communication over a common information model: an ontology [67,68].

To achieve syntactic interoperability, XML (eXtensible Markup Language) and JSON (JavaScript Object Notation) are frequently used as datasets over RESTful (Representational State Transfer) web services [69]. For the proposed EDISON serial-line based architecture, a RESTful web service has been developed on top of a Java web container running on a Raspberry Pi, acting as an application gateway between the proprietary serial-line protocol and HTTP [8]. Web services are rather resource intensive, typically operating on full-fledged microprocessors with an operating system. The MQTT (Message Queue Telemetry Transport) and CoAP (Constrained Application Protocol) protocols are more suitable for small microcontrollers as they are designed for more resource-constrained devices. These protocols are among others supported by Contiki open-source lightweight operating system and can be used on top of the EDISON IP-based solutions (Wireless and PLC).

These described protocols are heterogenous and appropriate action has to be taken to combine them. Protocol bindings can be created between all the available protocols. This rapidly becomes a tedious task as can be deducted from Formula 3, where N represents the number of protocols.

$$bindings = \sum_{i=1}^{N-1} i = \frac{N \times (N-1)}{2} \tag{3}$$

OneM2M offers a more convenient way. The OneM2M organization has a set of open standards supported by the world's preeminent standard development organizations. These standards utilize a horizontal architecture for achieving interoperability for M2M and IoT technologies [70]. Only one binding is required for each protocol towards the OneM2M base protocol, vastly simplifying communication over heterogenous networks. Semantic interoperability can be achieved on OneM2M compliant systems by using the OneM2M base ontology, or mapping towards this ontology.

The EDISON serial-line-based solutions have been integrated by developing an interworking proxy entity on the OneM2M compliant open-source Eclipse OM2M project. The situation is far simpler for EDISON IP-based solutions; they can use the MQTT, CoAP or even HTTP (HyperText Transfer Protocol) RESTful bindings for interacting with the horizontal OneM2M platform. Communication with other building automation protocols has not been thoroughly studied but can be realized by creating an Interworking Proxy Entity. This would allow interoperability with KNX, Zigbee, Z-Wave and other building and home automation protocols. A diagram is available in Figure 10.

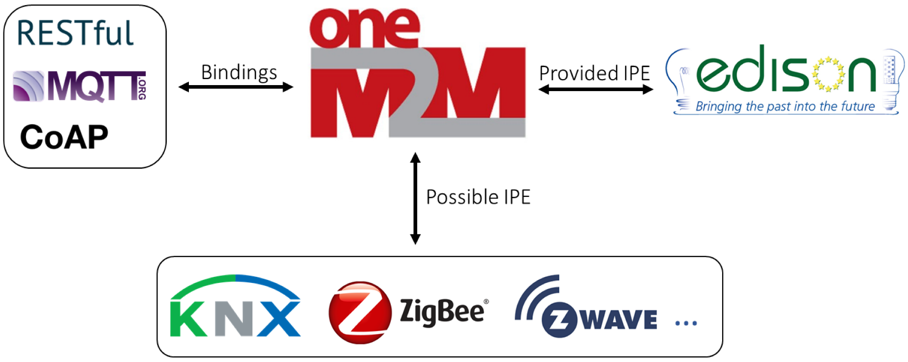

Figure 10. OneM2M horizontal Internet of things platform with supported bindings, provided EDISON Interworking Proxy Entity (IPE) and possible IPEs for home and building automation platforms.

6. The Complete EDISON DC-Based Lighting Architecture

In the previous chapters, several design choices made for the EDISON lighting system have been introduced. This section provides additional information and gives an overview of the global architecture. The goal is to realize a more efficient, safer, affordable and easy to maintain lighting infrastructure by migrating to a DC grid for feeding LED lamps. Tests have indicated that DC-based lighting can indeed be more efficient than AC-based lighting if appropriate installation rules are followed, as explained further. The lighting system's total energy consumption depends heavily on the efficiency of the utilized DC power supplies.

In the proposed EDISON DC-based lighting system, the operating voltage is chosen at 48 V_{DC} as a compromise between the ability to distribute power, the safety, and availability of supported devices. Some calculations should be performed when deploying the EDISON infrastructure. Whereas the LED lighting is more efficient and requires less energy than incandescent and fluorescent lamps for the same luminous flux, the 48 V_{DC} infrastructure requires higher currents to deliver this energy compared to its AC predecessor. The consequence is that cable losses play a substantial role on long cables with significant current or that the cable's rated current is even exceeded. This is mainly a concern in the case of retrofit, when existing cables are reused. The phenomenon is schematically presented in Figure 11a. These issues can be avoided by separating the lighting infrastructure in smaller sections and cleverly positioning the DC power supplies close to the lamps, utilizing the AC mains' superior distributing capabilities. The former allows lower currents and the latter allows shorter cables, both contributing to lower cable losses. It is schematically presented in Figure 11b.

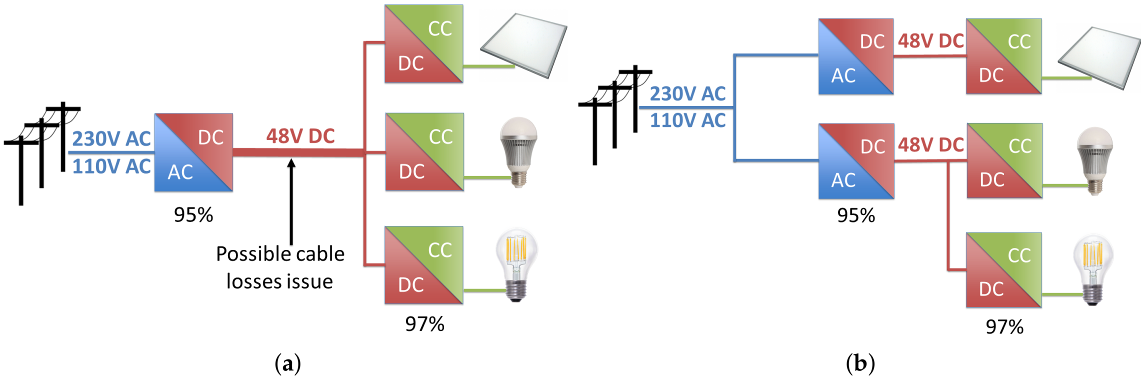

Figure 11. Two EDISON powering approaches. Approach b reduces the cable loss issue. (CC stands for constant current, which is provided by the LED drivers). (**a**) common 48 V_{DC} grid powering multiple zones; (**b**) multiple well located smaller and shorter 48 V_{DC} grids using AC mains as distribution backbone.

The energy consumption of the EDISON DC-based lighting infrastructure is monitored by using IP enabled smart energy meters. A multi-platform background process periodically collects this data for storage in a relational database. This allows checking live and historical energy consumption.

Connectivity within the EDISON system has been expanded over the years. The serial-based EDISON PowerLAN solution was the first to be supported. One or multiple Raspberry Pi lightweight computers are used as an application gateway between the PowerLAN's Modbus protocol and a RESTful web service [8]. This allows remote monitoring and control of the lighting system from any machine supporting the world wide web technology.

Recently, a more advanced solution has been created due to the increasing popularity of the Internet of Things and demand to achieve interoperability. IP-enabled communication devices simplify connectivity on the networking layer. Both an IEEE 802.15.4 based wireless solution, and a narrowband PLC solution operating on top of the 48 V_{DC} have been successfully deployed.

OneM2M facilitates interoperability between the EDISON lighting system and other systems. The MQTT and CoAP bindings allow direct communication between the EDISON IP-based solutions and the OneM2M infrastructure. A more complex solution is required for the PowerLAN solution. Here, the Raspberry Pi is shifted from having a RESTful web service into a OneM2M middle node. An interworking proxy entity (IPE) is used as application gateway towards the PowerLAN's Modbus protocol. In a similar fashion, the smart meter data is integrated into the OneM2M system: an IPE periodically checks the energy consumption database for updates. This complete OneM2M solution is depicted in Figure 12.

Pilot Results

Currently, over 100 EDISON systems have been deployed. One of the initial pilots is located at the student restaurant of the Vrije Universiteit Brussel. One area, originally lighted with 68 compact fluorescent bulbs and eight fluorescent tubes, has been retrofitted with a basic version of the EDISON system. A floor plan indicating the lighting zones, sensors and lamps is available in Figure 13. Luminance measurements have been performed before and after the retrofit, indicating an average luminance increment of 20%. The installation is divided in six on/off controllable zones and is equipped with 10 motion sensors. One area with daylight is furthermore equipped with a luminance sensor, allowing deactivation of the lighting when sufficient natural light is present. A smart meter has been fitted on the EDISON installation and measurements of the past 12 weeks have been aggregated in a database and have been analyzed.

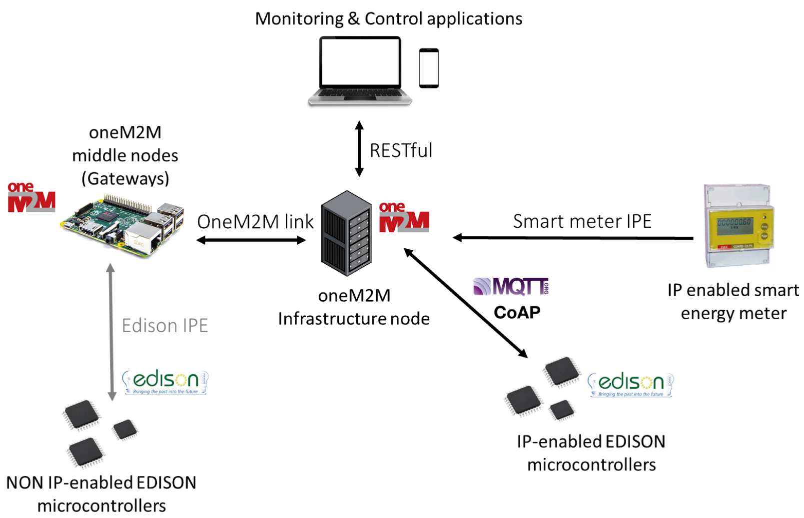

Figure 12. The complete EDISON solution with OneM2M.

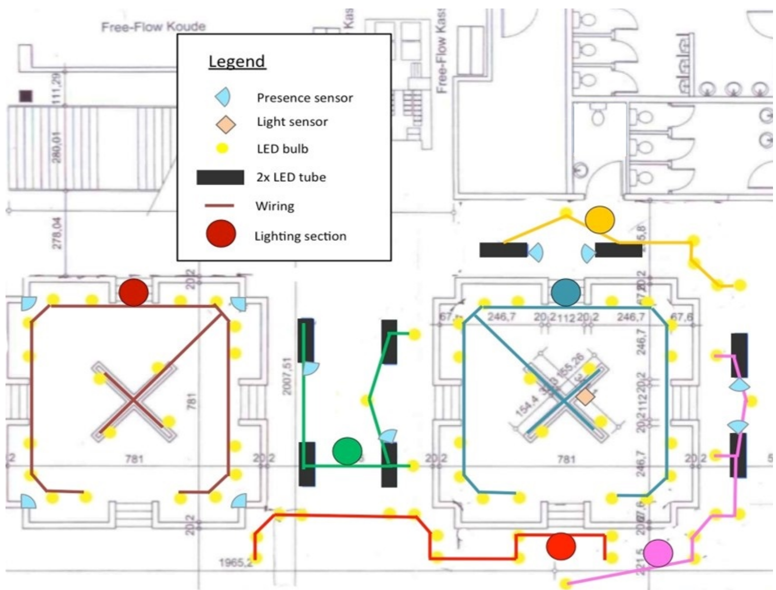

Figure 13. Floor plan of the lighting zones, sensors and lamps in the Vrije Universiteit Brussel restaurant EDISON pilot.

During these past 12 weeks, the EDISON lighting system has used 249.5 kWh. The lighting in the restaurant has been activated a total of 427.4 h during this period. The power consumption of the EDISON system with all the lighting activated is 732 W. From this information, it is possible to calculate total energy consumption without dimming by the smart components: 312.9 kWh. As such, an additional energy savings of 63.4 kWh has been achieved by the smart lighting control; this is 20.3% relative energy savings compared to the LED-based solution without smart control.

The power consumption of the original lighting infrastructure before the EDISON retrofit is also known to be 1780 W. Given the 427.4 operating hours, the original infrastructure would have used 760.8 kWh. The EDISON system with smart components allows an energy saving of 67.2% of the energy consumed by the original conventional lighting system based on compact fluorescent light bulbs and fluorescent tubes. Without smart components, their energy saving drops to 58.9%.

The pie chart in Figure 14 represents the relative ratios of the EDISON lighting system compared to the original infrastructure.

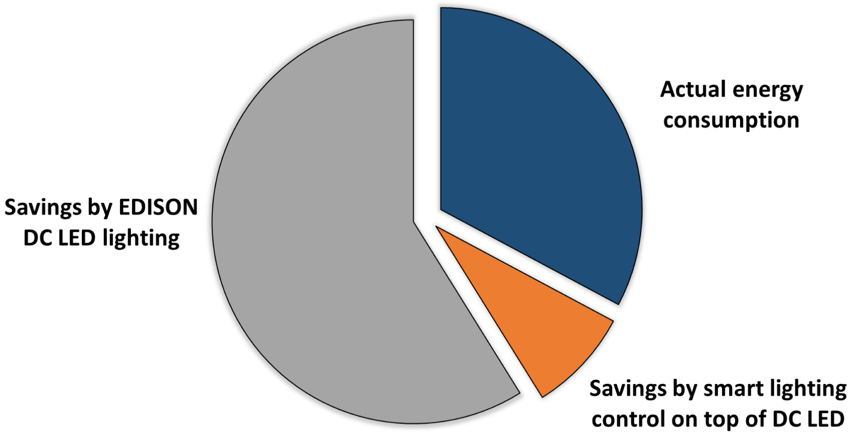

Figure 14. Pie chart representing actual energy consumption of the EDISON system, savings by migrating to DC-based LED lighting and savings by smart lighting control.

7. Conclusions

This paper guides the reader through the design choices for deploying DC or AC infrastructure destined for LED based lighting. It highlights basic concepts, reviews the most helpful and important sources of information and applies the obtained insights to qualitatively evaluate a DC- versus AC-powered solution. In the comparison, elements such as safety, regulatory aspects, reliability, complexity, ease of deployment and maintenance are taken into account. It is also strongly based on our own experience gained from building and exploiting several DC pilots on the VUB campus and in other sites in Europe. The comparison includes a thorough overview on how to organize smart lighting solutions with a strong focus on the communication infrastructure that supports smart lighting.

The paper motivates why DC is making a come-back and why it is well fit for organizing power transfer to the lamps. The EDISON solution uses a 48 V_{DC} system, as trade-off between distribution voltage, safety and device support. Measurements conducted on AC- and DC-powered LED drivers, and on 48 V_{DC} power supplies, indicate that a well-designed DC LED lighting solution can achieve superior efficiency over an AC solution. The retrofitting action performed in the VUB campus restaurant demonstrates that the DC-based, ICT (Information and Communications Technology) controlled lighting system operates flawlessly. It shows the energy savings mainly obtained from replacing compact fluorescent bulbs and fluorescent tubes into their DC-powered LED substitutes, and the extra savings obtained by dimming the lights when possible. Respectively, 59% and 67% of the energy is saved compared to the original lighting system. Aside from these energy savings, the new LED lamps provide a 20% increased illuminance level.

The paper also discusses in which way the proposed DC infrastructure used for LED lighting can play a role as a reliable, low latency communication channel. Such an infrastructure offers extra benefits as DC is fit for feeding the sensors and actuator boards, and allows more simple power line modems or use of the decommissioned third wire. The Internet Protocol is an enabler for realizing connectivity between devices on heterogeneous network solution, whereas OneM2M can facilitate horizontal integration between applications. Sensors initially useful for deciding how to steer the lights can also steer alarm systems or other actuators. The paper explains why it is beneficial to be able to mix wireless and wired technologies. It shows the role of gateways, the fog and the cloud for adding increased smartness, while taking into account maximum tolerable latencies for action to be taken.

Wireless technology as well as transporting information over the internet with storage and processing in the cloud raises security concerns. These have not been tackled in this paper and are surely considered as future work, in particular, for the OneM2M based horizontal integration. For this integration, a judicious development and choice of ontologies is also an important future research topic.

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